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Survival Stability of RoPax Reviewed In Terms of The Water on Deck (WoD)

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Abstract **- RoPax vessels are widely used worldwide but contribute to numerous fatalities. Accidents result from human factors, vessel damage, management, and natural causes. Vessel stability is a significant concern, with WoD leading to increased load and rising KG, potentially causing capsizing. This study examines a RoPax OCD UFP that experienced a WoD-related accident in Indonesian waters. Modifications considered are standard freeing ports, becoming RoPax OCD SFP, and applying side casings, or RoPax OCD WS assessed the Stockholm Agreement. Fluid simulation and stability failure criteria were employed at varying wave heights. The largest RAO on the variation of heading angle is changed into stability criteria, resulting in realistic outcomes that have not been seen in earlier research. The highest RAO roll occurs at a heading encounter angle of 60 degrees with a value of 2.192362 degrees/m. Results show survival for RoPax UFP, RoPax SFP, and RoPax WS in the 0-1 m wave height range, with only RoPax UFP capsizing at 2-3 m. RoPax WS has an extended stability arm but decreases stability at high wave heights. RoPax SFP is unaffected by WoD but may still face capsizing depending on the pure stability arm GZ factor. Modifying RoPax UFP to RoPax SFP or RoPax WS can improve survival intact stability.**

Keywords**:** *RoPax; Opened Car Deck (OCD); Water on Deck (WoD); Stability.*

NOMENCLATURE

RoRo	:Roll-on Roll-off
RoPax	:Roll-on Roll-off Passenger
OCD	:Opened Car Deck
WoD	:Water on Deck
UFP	:Standard Freeing Port (figure 4.a)
SFP	:Standard Freeing Port (figure 4.b)
WS	:With SideCasings (figure 4.c)
Hw	:Maximum wave height (m)
Hs	:Significant wave height (m)
T	:Wave period (second)
RAO	:Response Amplitude Operator (degree/m)
KG	:Keel to gravity (m)
GZ	:Righting lever arm (m)
SR	:Ship spectrum response
v	:Ship velocity (m/s)
g	:Gravity acceleration (m/s^2)
$S(\omega_e)$	:Encounter wave spectrum
ω_w	:Angular wave frequency (s^{-1})
ω_e	:Angular roll encountering frequency (s^{-1})
μ	:Heading angle (degree)
amax	:Maximum roll wave response (degree)
ξa	:Wave amplitude (m)
SOLAS	:Convention for the Safety of Life at Sea
IMO	:The International Maritime Organization
GT	:Gross Tonnage
MSC	:Maritime Safety Committee
B	:Buoyancy force (kN)
G	:Gravity force (kN)
VHM0	:Spectra wave height (m)
V_{TM01}	:Spectra wave period (second)
Σa_n	:Total area freeing port (m^2)
fr	:Freeboard
Lpp	:Length of per perpendicular (m)
Bmld	:Breadth molded (m)
Hmld	:Height molded (m)
T	:Draft (m)

I. INTRODUCTION

The weather conditions, such as wind and waves at sea, influence ships sailing. The weather has become a problem and a serious concern in recent years [1]. A suitable vessel should withstand various weather conditions according to the different states of its sailing routes and operational areas [2]. RoRo or RoPax is one of the most successful ships that can transport vehicles, cargo, and passengers in a single voyage [3]. These ships are widely operated by developing maritime nations for transportation between riverbanks, straits, and islands [3]. RoPax is one type of vessel that has caused the most significant number of accidents worldwide, requiring strict attention to reduce their occurrence [4]. Most ship accidents occur in developing countries such as Indonesia, the Philippines, and Bangladesh [5] [6].

The leading cause of these accidents is stability-related issues that cause the ship to capsize at sea. Small-sized RoPax ships have fundamental issues related to intact stability, while larger RoPax predominantly face damage stability problems. Small-sized RoPax, particularly those with RoPax OCD, are designed to minimize GT, and reduce the lightship and the need for air ventilation [7]. However, the design of the open vehicle deck makes it vulnerable to low freeboard and the occurrence of WoD

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[8]. On the other hand, there are no specific criteria that address stability issues for RoPax OCD ships.

Ship accidents are generally caused by three main factors: human error factors, internal ship condition factors, and external extreme weather conditions [5]. These factors can coincide as a single cause or in combination during an accident. Despite advancements in technology, processes, procedures, training, and regulations, a total of 193 vessels with a gross tonnage of over 100 GT were lost between 2014 and 2017, with sinking accidents (62%), grounding accidents (15%), fire/explosion accidents (10%), and machinery damage/failure accidents (6%) [9]. Human error accounts for 75% to 96% of the highest causes of ship accidents, and reducing it requires efforts to improve working conditions (appropriate working hours, fair wages, career opportunities, training, fresh air, and exercise) [10]. Total loss refers to a fatal ship accident that makes the ship irreparable. Based on the analysis of accident data from 1998 to 2018 involving 16 types of vessels, 13 sea regions, and 11 major accident factors, sinking, grounding, and fire/explosion were identified as the leading causes of total loss [11].

WoD is an event where water rises onto the deck and can lead to various disasters, causing RoPax OCD to capsize. Water rising onto the deck is due to the vehicle deck's lower height than the wave crest's height [12]. WoD can add load to the deck and create a free surface moment that increases the ship's KG. This moment is because the vehicle deck does not allow longitudinal and transverse bulkheads to be installed in the middle of the vessel, making the loading and unloading of vehicles more difficult. WoD events often occur gradually, with water entering the ship's compartments through access holes and leaky pipes. WoD issues in RoRo (Roll-on/Roll-off) vessels are a central part of the Stockholm Agreement (MSC Circ.1891 and EU directives) and have been included in the damage stability calculations in SOLAS 74/90 II-1/8 [13]. Unfortunately, SOLAS 2009 does not explicitly cover the Stockholm Agreement for the intact stability of minor RoPax OCD [10]. IMO is currently developing Second-Generation Intact Stability Criteria for ship safety, and one of the criteria being discussed is the vulnerability of low freeboard decks to WoD occurrences [14].

This paper discusses the influence of wave height, which leads to the vulnerability of WoD, thereby reducing the survival stability of the ship. The type of OCD ship studied is the RoPax that experienced an accident in Indonesian waters due to WoD (RoPax UFP), compared to if modifications were made with the application of a freeing port according to the Stockholm Agreement (RoPax SFP) and the implementation of side casings on the vehicle deck (RoPax WS). This paper aims to measure the survival stability of RoPax OCD with WoD under various wave height conditions to assess safe types of RoPax OCD and enhance the safety of existing and future RoPax OCD ships. The largest RAO on the variation of heading angle is changed into stability criteria, resulting in realistic outcomes that have not been seen in earlier research. It is expected that the safety of RoPax OCD continue to increase its survival.

II. LITERATUR REVIEW

IMO, regulators and classification societies require stability as one of the safety parameters throughout the design, construction, and operation of ships [15] [16]. In the ship design process, it is vital to understand the relationship between the ship's geometry and its stability characteristics [17]. The ship's stability arm GZ is calculated and evaluated during the preliminary design for various combinations of beam and draft ratios, freeboard-to-beam ratios, and center of gravity using IMO stability criteria. The evaluation results in minimum values for beam and draft ratios and freeboard-to-beam ratios that meet the IMO stability criteria. RoRo vessels have better stability as the beam and draft ratio increases [18].

Furthermore, ships with larger ones have better stability for the same beam and draft ratio. Ship stability improves as the freeboard-to-beam ratio increases. However, the influence of this ratio on ship stability is not significant when its value is less than 0.06. The freeboard-to-beam ratio influences substantial differences in stability characteristics when its value exceeds 0.10. These differences can be attributed to the ship's hull shape [19]. A vessel is a floating object that follows the principles of the balance of forces and the balance of moments. This balance of buoyant force is known as Archimedes' principle, where the weight of the ship is counteracted by an equal upward pressure called buoyancy. Moments occur due to the distance between the upward buoyant force and the downward weight force, forming the foundation of the ship's stability principle [20]. When the vessel is in a balanced state, with both weight (G) and buoyancy (B) forces aligned, but when an external force or moment is applied, the buoyancy force shifts position according to the shape of the immersed part of the ship in the water. When projected vertically, there is a distance between the two forces GZ, as seen in Figure 1 on the left. These two forces and the righting lever arm create a couple, supplying temporary stability to the ship. If the external force causes the ship to rotate back to its original position, it is called stable (positive GZ).

Conversely, if the ship rotates from its original position, it is called unstable (negative GZ), which can lead to capsizing. The righting arm GZ is depicted for each heel angle, representing the ship's stability. For a stable floating body, the GZ value is positive, starting from a heel angle of 0 degrees up to the vanishing/capsizing angle, as seen in Figure 1 on the right. For an unstable ship, the GZ value is negative, starting from a heel angle of 0 degrees. This condition should never occur during the design or operation of a vessel, as it poses a significant risk to the safety of passengers and cargo [21]. The principle of the GZ righting arm is varied for each heel angle, forming a curved graph with the x-axis representing the heel angle of the ship and the y-axis representing the length of the GZ stability moment, as shown in Figure 1.

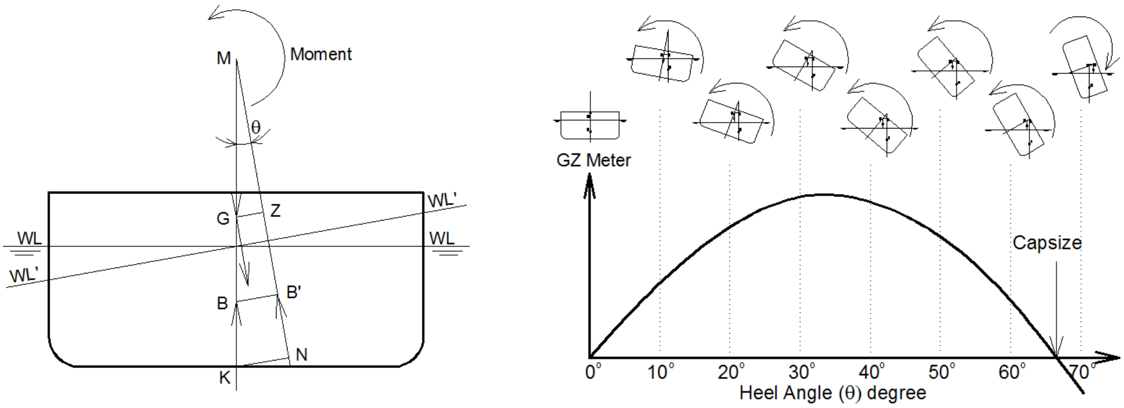

Figure 1. Principle of ship stability[22] [23]

The incident of WoD in small-sized OCD RoPax vessels can be compared to that of WoD in large-sized RoPax vessels that experience damage to the vehicle deck, and the difference lies in the type of water ingress. In OCD RoPax vessels, water ingress occurs through the freeing ports, which are supposed to drain water during calm conditions but become the entry point for water onto the deck. On the other hand, in large-sized RoPax vessels with a sealed vehicle deck, water ingress into the vehicle deck is caused by collisions or impacts that tear the ship's hull. Water ingress is a complex event to formulate, but it can be simplified using the modeling of Bernoulli's equations to measure ship stability and survival [24]. The incident of water reaching the vehicle deck occurs when water enters the deck due to high waves that exceed the openings in the ship's wall. The rise of water onto the deck imposes a load on the vessel, creating a free surface moment that can worsen the ship's stability. The incident of WoD often happens gradually, with the crew initially unaware of the situation until it becomes dangerously uncontrollable and affects the ship's stability, eventually leading to capsizing. This situation must be avoided and anticipated if it occurs on RoRo vessels [13]. RoRo vessels engaged in international travel are required to comply with Directive 2003/25/EC (also known as the Stockholm Agreement) and the amendment regulations of SOLAS 2020 [25] [26]. These standards are applicable only in Europe, and there is not enough detailed explanation for small-sized OCD RoPax vessels, resulting in most OCD RoPax vessels in Indonesia not meeting these requirements. Based on the Stockholm Agreement regulations, freeing ports, as shown in Figure 2, can prevent WoD incidents in RoRo vessels.

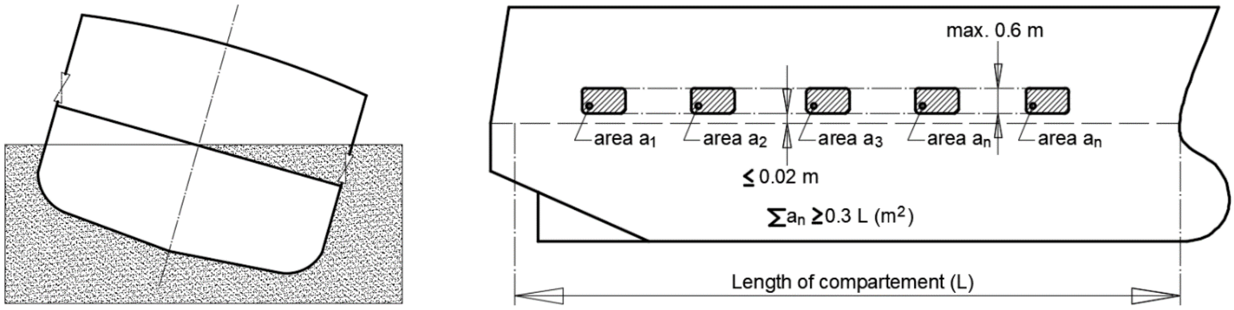

Figure 2. The area standard of freeing port does not affect the WoD [27].

The water-freeing ports on RoRo (roll-on/roll-off) vessels are openings on the vehicle deck side of the ship located above the waterline, used to drain seawater that enters the deck [28]. The freeing port area is sufficiently large to comply with regulations and prevents water accumulation, as water entering the deck can directly exit the ship, avoiding water on deck (WoD). The Stockholm Agreement governs the minimum freeing port area to avoid WoD on RoRo vessels, as depicted in Figure 2 [27]. The minimum freeing port area can be expressed in formula form as equation (1), where (a) represents the freeing port area, Sigma denotes the total area of the freeing ports, and L is the length of the RoPax compartments, as follows:

$$\sum a_n \geq 0.3\,L \tag{1}$$

WoD can occur if the port freeing area is less than 0.3L or does not satisfy equation (1) and if the wave height exceeds the deck height, causing water to enter the vehicle's deck. The amount of water entering the deck depends on the wave height outside the ship, which can be formulated using equation (2) as follows [27]:

$$\mathrm{Hs} = f(\mathrm{Hw}) = \frac{2}{3}\mathrm{Hw} \tag{2}$$

The calculation of the WoD in OCD RoPax is also influenced by the RoPax freeboard height, which is the difference between the deck height and the RoPax draft. The following are the effects of fr on it:

$$\mathrm{fr} \geq 2.0 \text{ m heigth WoD (hw)} = 0.0 \text{ m} \tag{3}$$

$$\mathrm{fr} < 0.3 \text{ m heigth WoD (hw)} = 0.5 \text{ m} \tag{4}$$

The high freeboard between the above provisions is interpolated linearly. The assumption for calculating the

Water on Deck (WoD) based on wave height (hs) is as follows:

Hs ≥ 4.0 m height WoD (hw) follow Figure 3 (5)

Hs < 0.3 m heigth WoD (hw) =0.0 m (6)

The high freeboard between the above provisions is achieved through linear interpolation. Figure 3 shows the wave height that causes the occurrence of WoD.

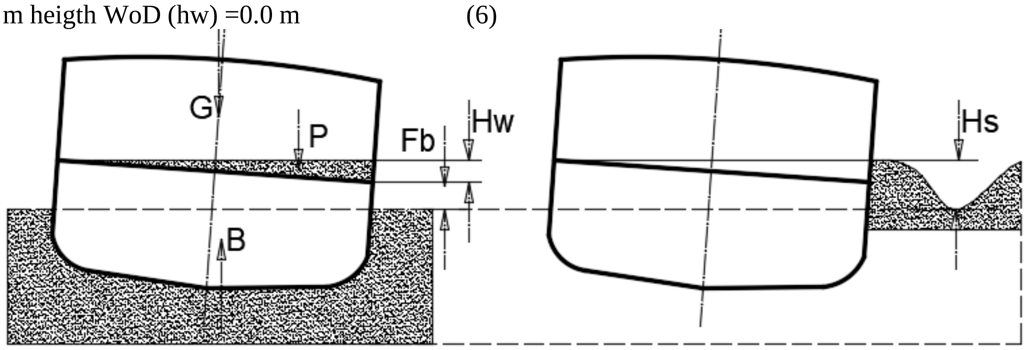

Figure 3. Influence of Hw on the height of WoD [27], [29].

The ship motions in the waves can be measured using RAO, a function of the structural movement amplitude relative to the wave amplitude. RAO can measure the stability of RoPax vessels using the Ince-Strutt chart [15]. Various methods to calculate the RAO include using a model in a towing tank, manually employing numerical or analytical approaches, or using specific software programs. Furthermore, the response of a structure in irregular waves can be estimated by transforming the wave spectrum into a response spectrum. The response spectrum is defined as the energy density response of the ship due to waves and can be calculated by multiplying the square of the RAO by the encountered wave spectrum. The mathematical equation for the floating body response can be expressed [30] [31]as:

$$S_R = [RAO(\omega_e)]^2 S(\omega_e) \quad (7)$$

Frequency and wave RAO for varying encounter heading angles can be calculated as follows [32] [33]:

$$\omega_e = \omega_e - \frac{\omega_w^2 v}{g} \cos(\mu) \quad (8)$$

$$a_{max} = RAO(\omega_e)_{max} * \xi_a \quad (9)$$

The most significant wave-induced roll response at specific frequencies and encounter angles can be related to the stability arm GZ when a ship experiences a Wheel-over-Deck (WoD) event. The goal is to use it as a criterion to decide whether the vessel capsizes or still is upright during a WoD event. If the angle exceeds the vanishing angle (the angle at which GZ starts to become negative), it can be confirmed that the ship capsizes. However, the RoPax (Roll-on/Roll-off Passenger) vessel remains upright if it has not yet reached the vanishing angle.

III. METHOD

This paper discusses the influence of wave height that causes vulnerability to the occurrence of WoD, thus reducing the survival stability of a RoPax vessel involved in an accident in Indonesian waters due to WoD (RoPax UFP), compared to the modification of implementing freeing ports according to the Stockholm Agreement (RoPax SFP) and the application of side casings on the vehicle deck (RoPax WS). A research method was developed, as shown in Figure 3, to achieve this objective. The technical data collected includes the technical specifications and environmental information on wave height, period, and direction. The RoPax OCD technical data was collected from the Intact Stability Booklet. From this data, the RoPax OCD is modeled using computer software, such as the hull modeling, load, and wave condition. After that, the stability of the vessel was calculated for three types: RoPax Unstandardized Freeing Port (RoPax UFP), RoPax Standardized Freeing Port (RoPax SFP), and RoPax with Sidecasings (RoPax WS) (see Figure 4). The third RAO of the RoPax are calculated with varying heading angles of 30 degrees, 60 degrees, 90 degrees, 120 degrees, and 150 degrees. WoD and the angle RAO calculate wave height at 0 m, 1 m, 2m, and 3 m. The calculation results were then analyzed by comparing these three types of vessels to determine the best survival stability of RoPax. The analysis results recommended reducing the risk of accidents involving RoPax OCD vessels in Indonesian waters.

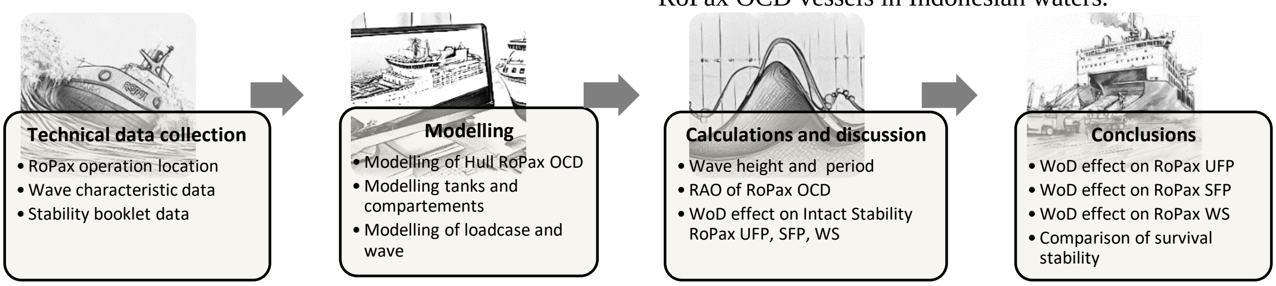

Figure 3. Paper research method

The case study in this research is about the RoPax OCD accident on August 15th, 2018, in the waters of Loloda, Halmahera Island, due to a WoD problem that affected the stability, causing it to capsize and sink. This accident is one of the tragic maritime incidents that happened in Indonesia. During this unfortunate event, the

RoPax OCD carried forty-five passengers; five were declared missing and have not been found. Four of them were crew members, and one was a passenger. The joint search and rescue team continues to search for the victims with the aid of fishing boats and patrol ships. The case study paper discusses the hull form of the RoPax OCD, which lacks side casings and freeing ports that do not follow the standards of Directive 2003/25/EC (also known as the Stockholm Agreement) and the regulations of the SOLAS 2020 amendment [27]. The main dimensions of the RoPax OCD are in Table 1.

TABLE 1
MAIN DIMENSIONS ROPAX OCD CASE STUDY

Dimensions	Unit	Value
Lpp	meter	45
B	meter	10
H	meter	3,5
T	meter	2,5

The RoPax case study has resulted in a reduced reserve buoyancy and an increased risk of WoD, thus affecting the survival stability of the ship. A comparison of the three types of RoPax OCD can be seen in Figure 4 as follows:

a. RoPax Unstandar Freeing Port (RoPax UFP)

b. RoPax Standard Freeing Port (RoPax SFP)

c. RoPax With Sidecasings (RoPax WS)

Figure 4. The RoPax case study variations.

Figure 4 above generally shows that the image in the left column stands for a front perspective view, while the image in the right column shows the RoPax OCD from the side. In Figure 4.a, the top row depicts the RoPax OCD with non-standard freeing ports with a hole height of 100 mm. The freeing ports cause water to enter the vehicle deck quickly but make it difficult to exit, resulting in WoD. In Figure 4.b, the middle row illustrates the RoPax OCD with standard freeing ports according to the Stockholm Agreement, which have a hole height of 600 mm. The freeing ports allow water to quickly enter and exit the vehicle deck, preventing the occurrence of WoD.

In Figure 4.c, the bottom row shows the RoPax OCD with side casings, which have a side casing height of 2.4 meters along the vehicle deck and a width of 2 meters from the deck's edge. Sponsons or side casings can improve seakeeping quality, safety, and comfort [34]. Furthermore, the side casings improve intact stability, but in high waves and angles exceeding the side casings, WoD may occur. Moreover, calculations and discussions are being conducted for the three types mentioned above of RoPax OCD models.

III. Results and Discussion

This section discusses wave propagation conditions during the RoPax OCD accident case study, wave response RAO for various heading angles, and ship stability conditions under different wave heights. The stability analysis of the RoPax OCD ship is conducted to decide the influence of WoD on the reduction of ship stability, which leads to accidents. Various wave heights are used, including 0 meters, 1 meter, 2 meters, and 3 meters. Furthermore, a comparison is made between the water wave conditions and stability for three types of ships, as shown in Figure 4. For more details, please refer to the following discussion.

The case study of the RoPax OCD accident occurred on August 15th, 2018, in the waters of Loloda, Halmahera Island. In August, Indonesia is in the dry season, and the sea waves during this month are usually calmer than in other months. High wave height maps globally were obtained from reanalysis waves on Copernicus [21], and then they were visualized using Ocean Data View software, shown in Figure 4. Several factors influence the season and waves in August in Indonesia. Geographic location influence: Indonesia is in a tropical region with a strategic position between two major oceans, the Pacific and the Indian Ocean. This location influences Indonesia through winds and ocean currents that shape its climate and wave patterns [35]. Monsoonal wind movement: In August, Indonesia is controlled by the southwest monsoon winds from Australia, which bring dry air and cause low rainfall in most parts of Indonesia. These winds also affect the sea wave conditions along Indonesia's southern and western coasts, which tend to be calm.

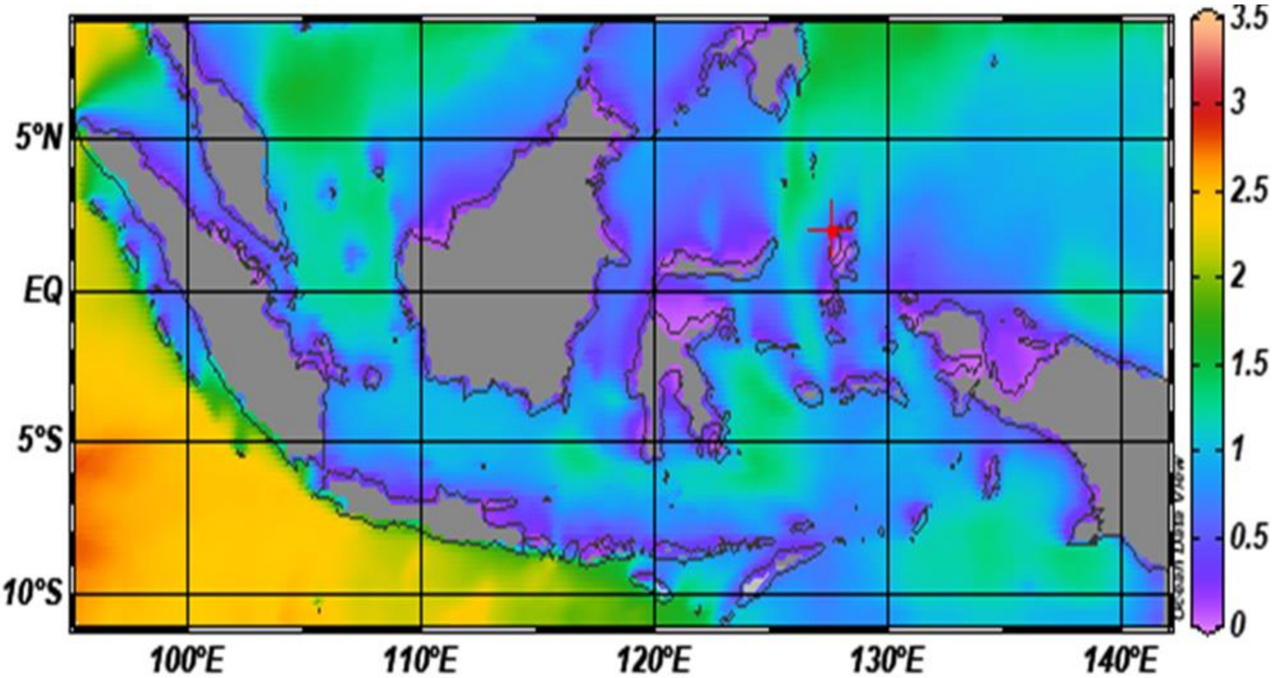

Figure 4. Indonesia wave characteristics when the case study RoPax capsizing [21]

The map Figure 5 above shows that Indonesian waters have a wide range of wave heights, ranging from 0 to 3.5 meters. However, upon closer examination, there are significant differences in wave height in certain maritime regions. The northwestern waters outside the open islands have wave heights ranging from 2 to 3.5 meters. The waves may be due to the influence of monsoon winds or the geographical conditions of that area. Meanwhile, wave heights in enclosed waters such as bays or straits surrounded by islands tend to be smaller, ranging from 0 to 2 meters. The islands may be attributed to the natural protection provided by the islands, which can dampen wave strength. Detailed ship navigation route maps are crucial in cases of ship accidents, as in the case of the RoPax OCD vessel, as they can supply accurate modeling of the ship's route, accident points, and wave heights at the time of the incident, which are essential factors in ship accidents. In this case study, the detailed ship navigation route map of the RoPax OCD vessel from Tobelo, North Halmahera, to Bitung City, North Sulawesi, is shown by a (+) symbol in Figure 6. Furthermore, the wave characteristics at the location of the ship accident can be seen in Figure 7 as follows:

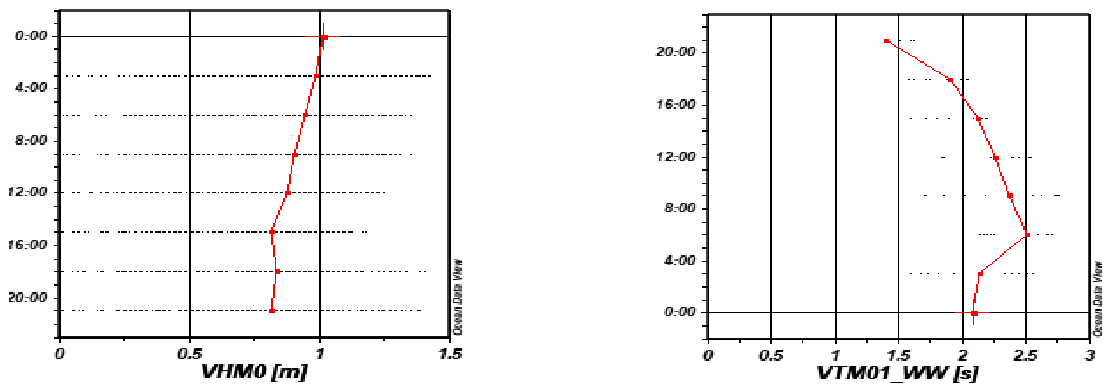

Figure 6. Wave height and period on the sea location when the case study RoPax capsizing [21]

The analysis of Figure 7 on the left shows that the significant wave height during the event ranged between 0.68 and 1.02 meters, or when converted to the maximum wave height, between 1.02 and 1.53 meters. This wave height range falls within sea state 2 (two), with wind speeds ranging from 4 to 6 knots. Sea state is defined as the level of roughness of the sea surface measured based on the significant wave height and average wind speed above the sea surface. Wave period refers to the time a wave takes to complete one cycle. Figure 7 on the right stands for the wave period ranging from 1.4 to 2.5 seconds in the waters of Loloda, Halmahera Island, during the event. Based on the research by Prasetyo [36], the wave height is classified as zone II or the second zone, which falls within the L area and is 50 meters from the coast.

A. RAO Roll of RoPax OCD

RAO is one of the essential parameters in ship seakeeping. This parameter describes the floating body of motion response to waves at a specific frequency. In the case of the RoPax OCD ship, RAO can be calculated for various ship motions, such as roll, pitch, and heave. RAO rolls can indicate ship safety because excessive roll motion beyond the vanishing angle can lead to the floating body capsizing. In the research conducted, the calculation of the RAO rolls for the RoPax OCD ship showed different values for various heading variations: 30 degrees, 60 degrees, 90 degrees, 120 degrees, and 150 degrees. RAO shows that the RoPax OCD ship has good stability in facing waves at different heading angles. Furthermore, the research results also show that the RAO of all types of RoPax ships, including RoPax UFP, RoPax SFP, and RoPax WS, have the same results because they have the same hull shape below the waterline, and the assumption is that modifications on the vehicle deck do not add weight or change the floating body center of gravity. The calculation of the RAO roll is presented in the form of a graph as follows:

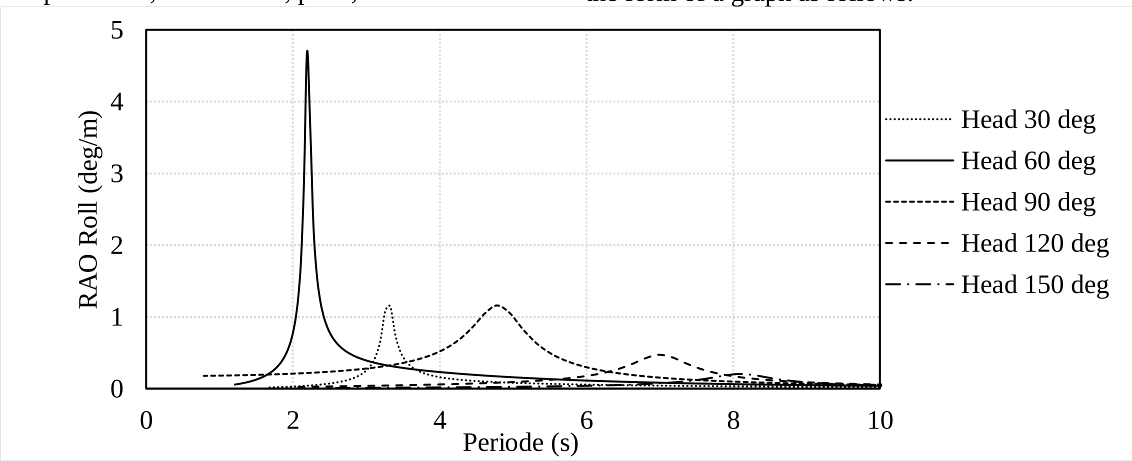

Figure 5. RAO rolls at various heading angles.

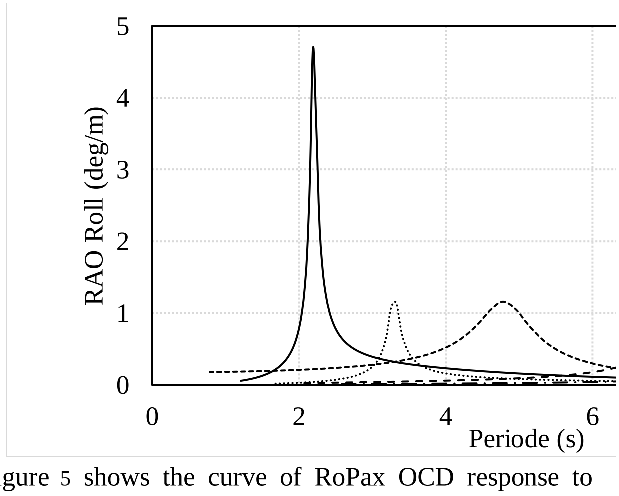

Figure 5 shows the curve of RoPax OCD response to ocean waves, expressed as RAO versus wave period for varying heading encounter angles. First, at a heading encounter angle of 30 degrees, the peak period occurs at a value of 1.145965 seconds, and the highest RAO roll also occurs at that angle with a value of 3.326853 degrees/m. Second, at a heading encounter angle of 60 degrees, the most significant period occurs at a matter of 4.69287 seconds, and the highest RAO roll occurs at that angle with a value of 2.192362 degrees/m. Third, at a heading encounter angle of 90 degrees, the most considerable period occurs at a matter of 1.158554 seconds, and the highest RAO roll occurs at that angle with a value of 4.780684 degrees/m. Fourth, at a heading encounter angle of 120 degrees, the most prominent period occurs at a discount of 0.471201 seconds, and the highest RAO roll occurs at that angle of 6.976061 degrees/m. Fifth, at a heading encounter angle of 150 degrees, the most extensive period occurs at 0.203373 seconds, and the highest RAO roll occurs at that angle with a value of 8.068391 degrees/m. From the comparison of the highest RAO roll values at each heading encounter angle, it can be concluded that the highest RAO roll occurs at a heading encounter angle of 60 degrees with a value of 2.192362 degrees/m. The curves show that the floating body is more sensitive to ocean waves coming from that direction. Based on the information obtained from the authorities, it was found that during the accident, the RoPax OCD in the case study departed from Tobelo towards Belitung at 20:00 local time. However, the ship changed course shortly after and returned to Tobelo due to severe weather [20]. Therefore, it is highly likely that the vessel experienced the giant RAO roll with a wave heading 60 degrees from the astern beam sea direction.

B. Stability Survival of WoD Effect on Wave Height 0 m

Stability criteria are one of the crucial factors that must be fulfilled in the design and operation of ships. Because stability is a determining factor for capsizing safety, this section analyzes the stability of RoPax UFP, RoPax SFP, and RoPax WS ships in calm waters. This comparison is made to compare the level of stability of the three types of ships, which are displayed in the form of graphs as follows:

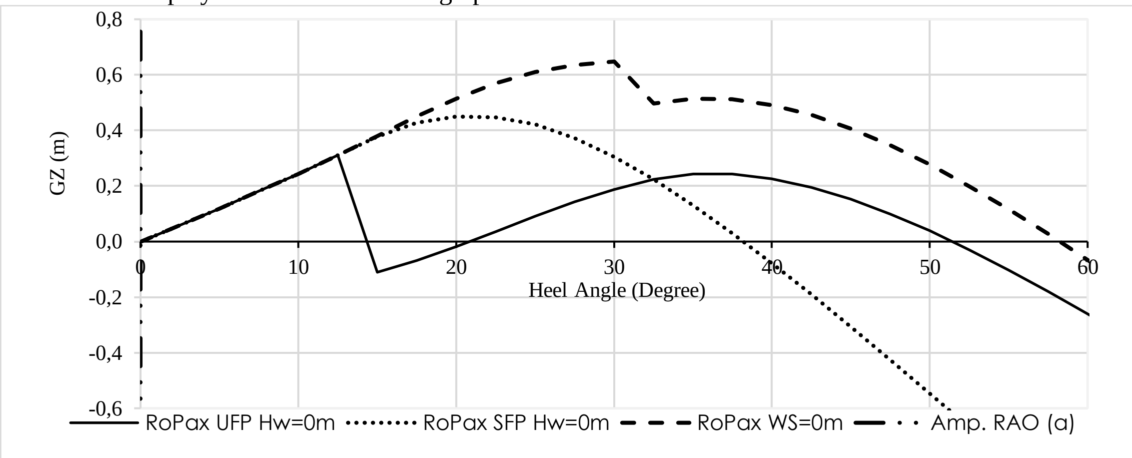

Figure 8. The Effect of WoD on wave height is zero meters, affecting the stability of survival GZ.

Figure 8 above shows the stability arm curve of three types of RoPax vessels: RoPax UFP, RoPax SFP, and RoPax WS. The stability arm curve is calculated at Hw=0 meters, meaning no wave. The solid line curve stands for the stability arm curve of RoPax UFP, the round dot curve represents the stability arm curve of RoPax SFP, the dashed curve represents the stability arm curve of RoPax WS, and the double dot curve represents the highest amplitude angle of RAO or (a). The stability arm curve of RoPax UFP has a positive value of 0~14.9 degrees, then decreases to negative and becomes positive again in the angle range of 20.879 ~ 51.59 degrees. The most significant angle is 12.5 degrees, and the ultimate arm reaches 0.311 meters. The stability arm curve of RoPax SFP has a positive value from 0 ~ 38.45 degrees. The most significant angle is 20 degrees, and the top arm reaches 0.45 meters.

Meanwhile, the stability arm curve of RoPax WS has a positive value from 0 degrees to 58.226 degrees. The most significant angle is 30 degrees, and the leading arm reaches 0.648 meters. Based on the graph, the survival stability of RoPax WS is the highest, followed by RoPax SFP and RoPax UFP. The curve shows that RoPax WS is more stable in calm water conditions than RoPax SFP and RoPax UFP. From the calculation results of the influence of WoD connected to Hw=0 m, the value of RAO is obtained as 4.780684 (degree/m), so the amplitude RAO [a] can be calculated as [a] =RAO*ξ_a= 0 degrees. The vanishing angle of RoPax UFP, RoPax SFP, and RoPax WS is not too large, writing down that all types of vessels can survive.

C. *Stability Survival of WoD Effect on Wave Height 1 m*

This section conducts a wave height 1-meter analysis of the stability of RoPax UFP, RoPax SFP, and RoPax WS ships. This comparison of the WoD effect is made to compare the level of survival stability of the three types of vessels, which are displayed in the form of Figure 9 as follows:

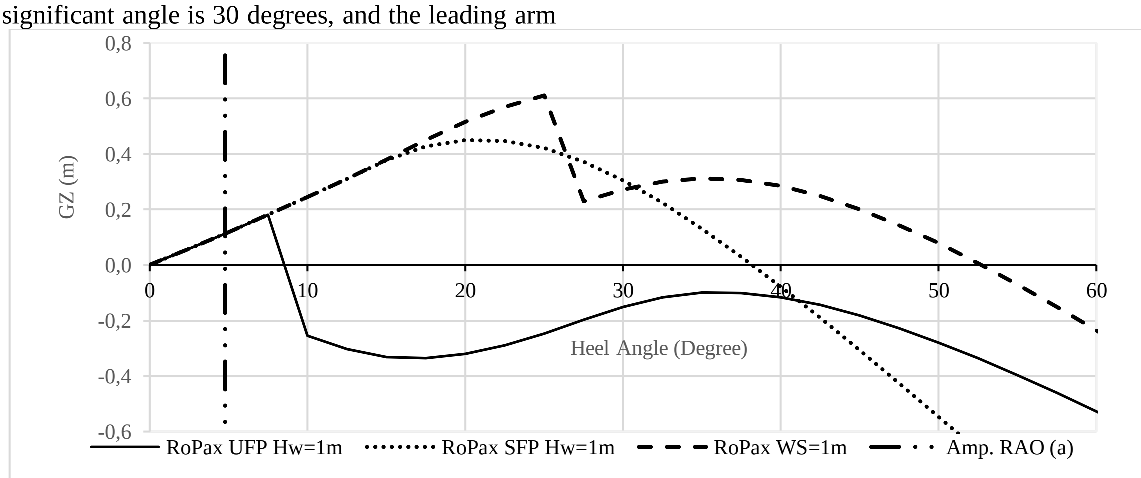

Figure 9. The Effect of the WoD on wave height is one meter, affecting the stability of survival GZ.

Figure 9 above shows the stability arm curve of three types of RoPax ships: RoPax UFP, RoPax SFP, and RoPax WS. The stability arm curve is calculated at Hw = 1 meter. The stability arm curve of RoPax UFP shows positive values from 0 ~ 8.537 degrees, and then the angle decreases and becomes negative. On the other hand, the stability arm curve of RoPax SFP has positive values from 0 ~ 14.9 degrees, with the most significant angle occurring at 20 degrees and a leading arm of 0.45 meters. The stability arm curve of RoPax WS has positive values from 0 ~ 52.72 degrees, with the most significant angle occurring at 25 degrees and an ultimate arm of 0.611 meters. The curve says that RoPax WS has the highest survival stability compared to RoPax SFP and RoPax

UFP. From the calculation results of the influence of WoD at Hw = 1 meter, the RAO value is obtained as 4.780684 (degrees/m). Therefore, as [a] =RAO*ξ_a= 4.780684 * 1 = 4.780684 degrees, where the vanishing angle of RoPax UFP, RoPax SFP, and RoPax WS is not excessive, ensuring the survival of all ship types.

D. Stability Survival of WoD Effect on Wave Height 2 m

This section conducts a wave height 2-meter analysis of the stability of RoPax UFP, RoPax SFP, and RoPax WS ships. The wave height is two meters near the RoPax OCD case study, capsizing appropriate analysis section 4.1. This comparison of the WoD effect is made to compare the level of the GZ stability of the three types of vessels, which are displayed in the form of Figure 10 as follows:

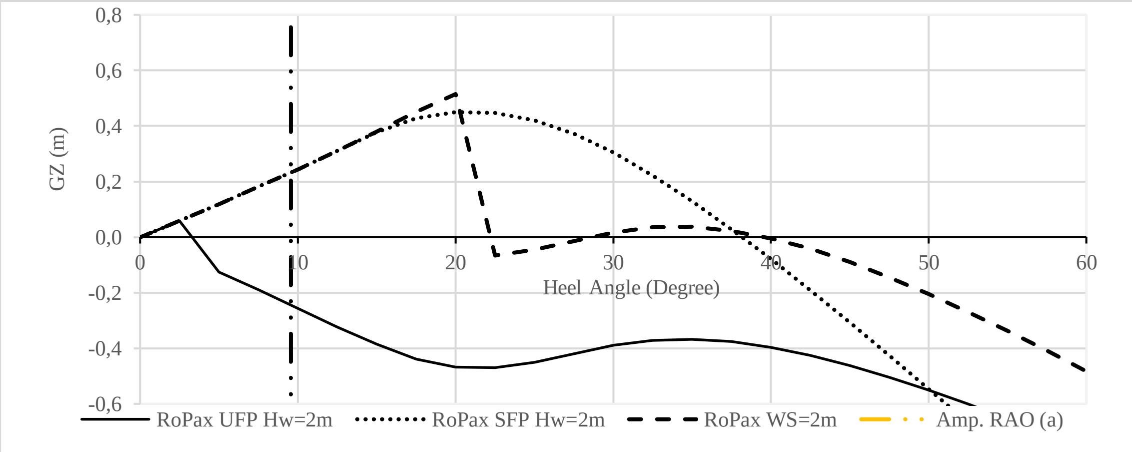

Figure 10. The Effect of the WoD on wave height is two meters, impacting the stability of survival GZ.

Figure 10 above shows the wave height conditions during the case study vessel. The calculation of the stability arm curve is performed at Hw=2 meters. The stability arm curve of RoPax UFP has positive values from 0 degrees to an angle of 9.7 degrees, and then the curve decreases and becomes negative. On the other hand, the stability arm curves of RoPax SFP and RoPax WS have positive values from 0 degrees to 20 degrees. In RoPax SFP, the most significant angle occurs at 38.17 degrees with a top arm of 0.45 meters. In RoPax WS, the most considerable curve occurs at 20 degrees with the same ultimate arm of 0.45 meters. The graph shows that the survival stability of RoPax WS has the highest value compared to RoPax SFP and RoPax UFP. The curve indicates that RoPax WS can remain stable in more extreme wave height conditions than RoPax SFP and RoPax UFP. From the calculation results of the influence of WoD connected to Hw=2 meter, the RAO value is obtained as 4.780684 (degrees/m), so the RAO amplitude [a] can be calculated as [a] =RAO*ξ_a =4.780684*2 = 9.561368 degrees. The vanishing angle of RoPax SFP > [a] so the vessel survives. Furthermore, the vanishing RoPax WS > [a], so the RoPax stays too. However, for the angle vanishing RoPax UFP < [a], the RoPax capsizes. The vanishing heel GZ of RoPax UFP is too low, causing this type of RoPax to be inverted while RoPax SFP and RoPax UFP survive.

E. Stability Survival of WoD Effect on Wave Height 3 m

This section conducts a wave height 3-meter analysis of the stability of RoPax UFP, RoPax SFP, and RoPax WS ships. This comparison of the WoD effect is made to compare the level of survival stability of the three types of vessels, which are displayed in Figure 11 as follows:

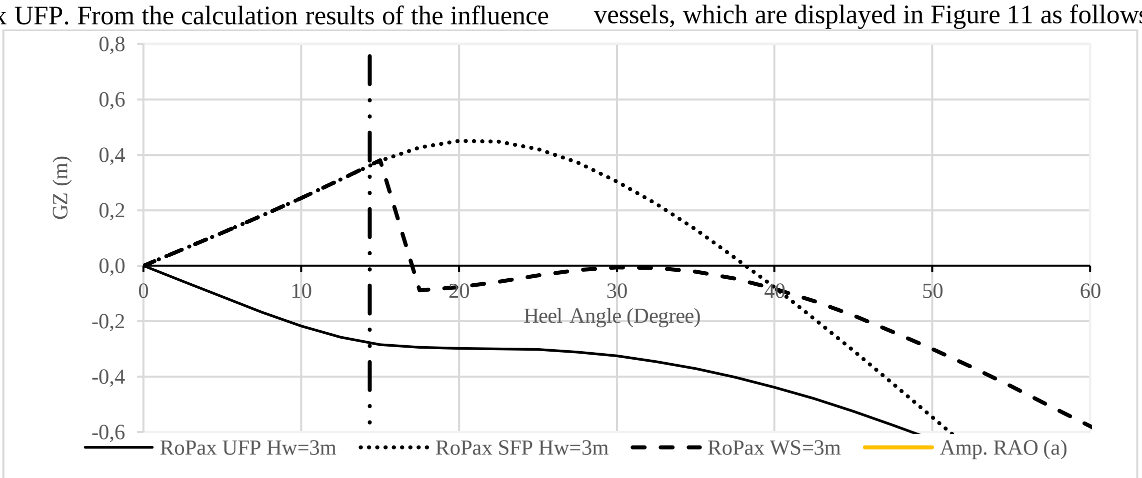

Figure 11. The effect of the WoD on wave height is three meters, changing the stability of survival GZ.

Figure 11 curves above show the calculation of the stability curve arm at a wave height (Hw) of 3 meters. Three angles are displayed: RoPax UFP, RoPax SFP, and RoPax WS curves. The RoPax UFP curve says the stability arm is directly minus, starting from 0 degrees. On the other hand, both the RoPax SFP and RoPax WS curves have positive values starting from 0 degrees up to the most significant angle. The maximum GZ is 20 degrees on the RoPax SFP curve with an ultimate arm of 0.45 meters. Meanwhile, on the RoPax WS curve, the most significant angle occurs at 16.4 degrees with a top arm of 0.38 meters. From the graph, it can be concluded that the survival stability of RoPax WS is the highest, followed by RoPax SFP and RoPax UFP.

Calculating the stability curve arm is crucial in determining the RoPax stability when facing waves. By knowing the stability arm, it can be calculated whether the ship capsizes or not. Therefore, the stability curve arm must be calculated carefully and accurately to ensure the RoPax OCD and its passengers are safe. From the calculation results of the effect of WoD concerning Hw = 3m, the RAO value is obtained as 4.780684 (degree/m). Therefore, the RAO amplitude [a] can be calculated as [a] =RAO*ξ_a= 4.780684 * 3 = 14.342052 degrees, where the vanishing angle of RoPax UFP is excessive, resulting in this type of RoPax being inverted, while RoPax SFP and RoPax UFP survive.

CONCLUSIONS

Based on the analysis conducted, it can be concluded that stability is an essential factor in ensuring the safety of a ship, as it can be used to measure the RoPax OCD survivability. This study examines the stability of three diverse types of RoPax vessels: RoPax UFP, RoPax SFP, and RoPax WS, with various wave heights Hw=0m, Hw=1m, Hw=2m, and Hw=3m. The calculation results and analysis lead to the following conclusions:

- Stability is vital in assessing the safety of a RoPax OCD risk of capsizing, which must always be controlled from the RoPax OCD design, production, and operation. RoPax OCD is a critical vessel in the global transportation system, capable of carrying multiple cargoes simultaneously with a spacious vehicle deck, making it highly susceptible to WoD that can compromise the RoPax OCD stability.
- Through reanalysis of wave characteristics at the location and time of the RoPax accident case study, Hs ranging from 0.68 to 1.02 meters is obtained, or when converted to the enormous wave height, it ranges from 1.02 to 1.53 meters—the wave period ranged from 1.4 to 2.5 seconds. The size and period of waves in this range are considered low, corresponding to sea state 2, as the location is in enclosed waters and close to the coast.
- RAO roll calculations were performed with heading angles of 30 degrees, 60 degrees, 90 degrees, 120 degrees, and 150 degrees. The heading angle of 60 degrees yielded the highest RAO roll response at 4.780684 degrees/m. This heading angle of 60 degrees is highly possible because the ship was returning to its original port during the incident.
- At Hw = 0-1 m, connected to WoD and stability, it is found that RoPax UFP, RoPax SFP, and RoPax WS all survive. However, at Hw = 2-3 m, it is found that only RoPax UFP capsizes. RoPax WS has the longest and highest range of stability arm GZ, but it drops after WoD occurs once the wave height exceeds the height of the side casings. RoPax SFP is not affected by WoD, so the capsize effect depends on the angle amplitude of ROA [a].
- From the RoPax UFP, a case study of an accident where the most significant wave height is plotted at 1.53 meters and the wave period is 2.5 seconds, it is obtained that RAO = 4.780684 degrees/m. The Hw at the time of the incident can be interpolated in the calculation of the effect of WoD on stability at Hw = 1 m and 2 m. It is found that the amplitude of RAO [a] > vanishing angle = (7.3144 > 6.944) degrees, so it can be concluded that there is a match between the calculation and the fact that the ship capsizes and sinks.
- To improve the survival stability of RoPax UFP, the RoPax OCD modifications can be made to transform it into RoPax SFP and RoPax WS, which have longer and higher survival stability arm curves. Suppose the solution of RoPax SFP is used. In that case, although it is safer, it has the drawback of allowing water to enter and exit quickly, potentially damaging the cargo on the vehicle deck. If the solution of RoPax WS is used, it has the disadvantage of reducing the area of the vehicle deck, and when the wave height exceeds the height of the side casings, the RoPax OCD stability drops at once.

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